Seasonal forecasts of carbon and water on land

Eunjee Lee

University of Maryland, Baltimore County / NASA Goddard Space Flight Center

Randal D. Koster (NASA), Yuna Lim (UMBC/NASA), Jana Kolassa (SSAI/NASA), Yujin Zeng (UMBC/NASA), Mauricio Arias (USF)

National Aeronautics and Space Administration

Global Modeling and Assimilation Office
gmao.gsfc.nasa.gov

Overview

1. Quick introduction to Land Surface Model (LSM)

2. Subseasonal-to-seasonal (S2S) forecast of meteorology

2. Sub-seasonal water forecasts to support for decision-making processes
    - Improved forecast skill of streamflow at southeast Asian rivers

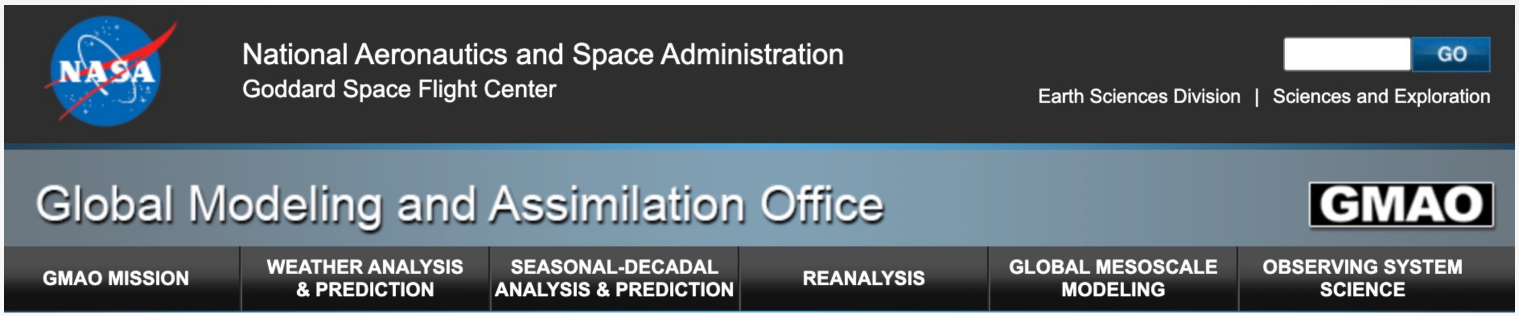
3. Seasonal forecast of land's carbon uptake
    - Predictability of gross primary productivity (GPP)

NASA Goddard Space Flight Center

- Located outside Washington D.C. (Greenbelt, Maryland)
- Earth Sciences Division (ESD)
  - Global Modeling and Assimilation Office
  - Laboratories that study the atmosphere, the hydrosphere, the biosphere, and geophysics

Global Modeling and Assimilation Office (GMAO)

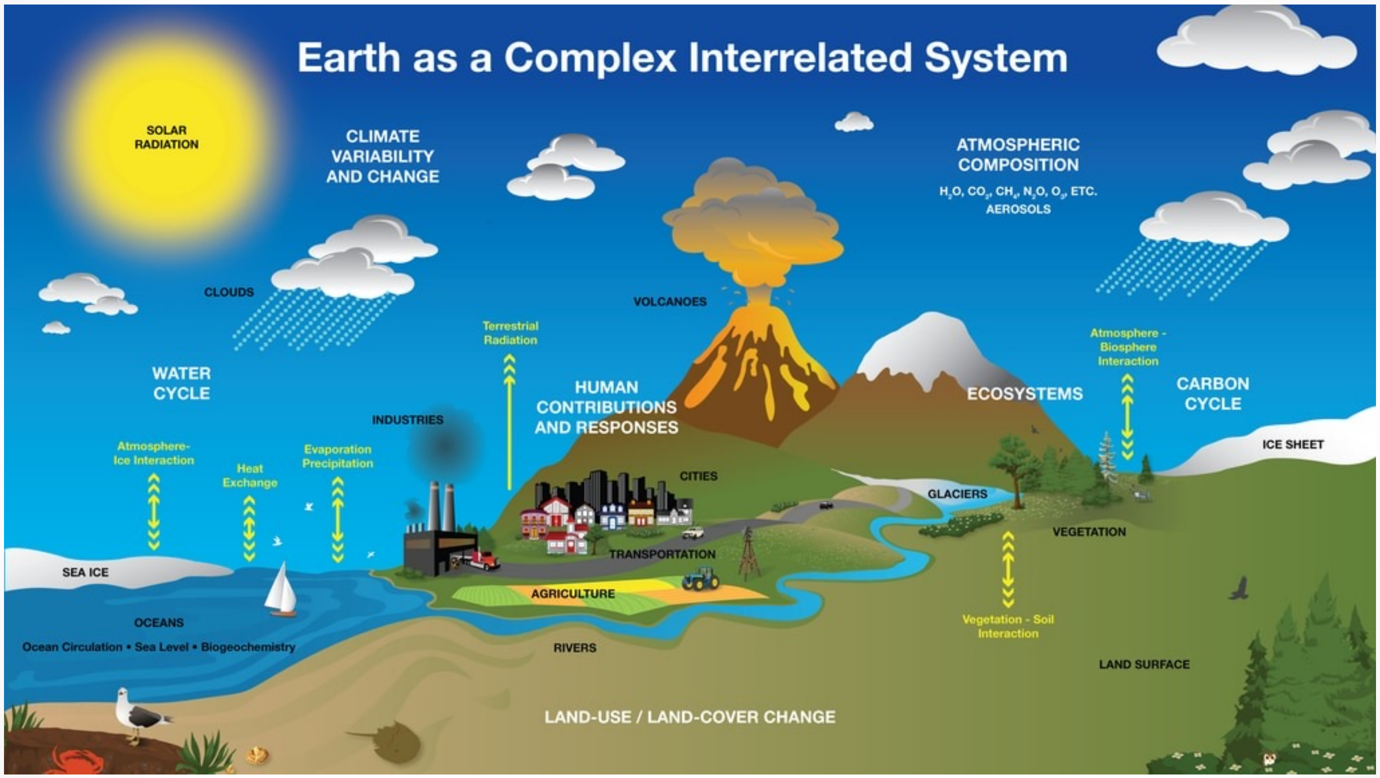
National Aeronautics and Space Administration



- NASA GMAO's research activities
  - Development of NASA's Earth System Model
    - Global Earth Observing System (GEOS) model
  - Weather analysis and prediction, Seasonal-decadal analysis and prediction, Reanalysis, Global mesoscale modeling, Observing system science
- Major products
  - MERRA-2 reanalysis meteorology (1980-present)
  - GEOS subseasonal-to-seasonal (S2S) hindcast and forecast meteorology

Modeling the Earth system

National Aeronautics and
Space Administration



https://mynasadata.larc.nasa.gov/basic-page/earth-system-matter-and-energy-cycles

Modeling the future of the Earth system

Modeling tools are useful for:

- Exploring underlying mechanisms of what we observe in the Earth system
- **Forecasting/projecting the future states** of the Earth system

Earth System Models (ESM) are used to forecast of the future status of the Earth system:

- Coupled model Intercomparison Projects to support IPCC Assessment Reports
- Subseasonal-to-seasonal forecasts

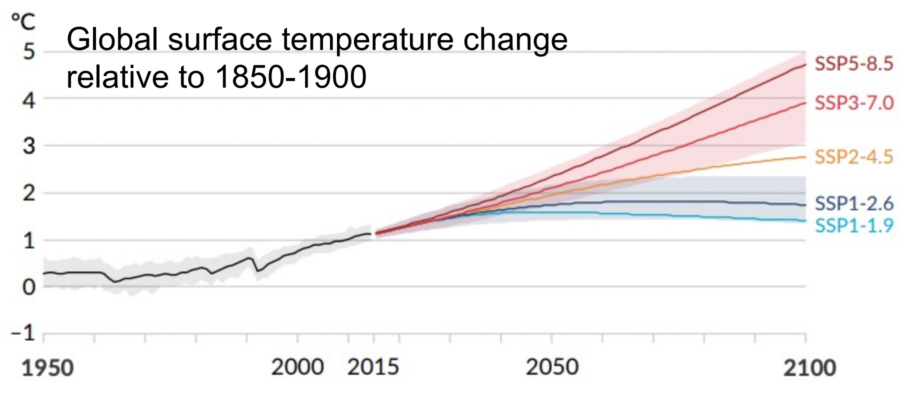
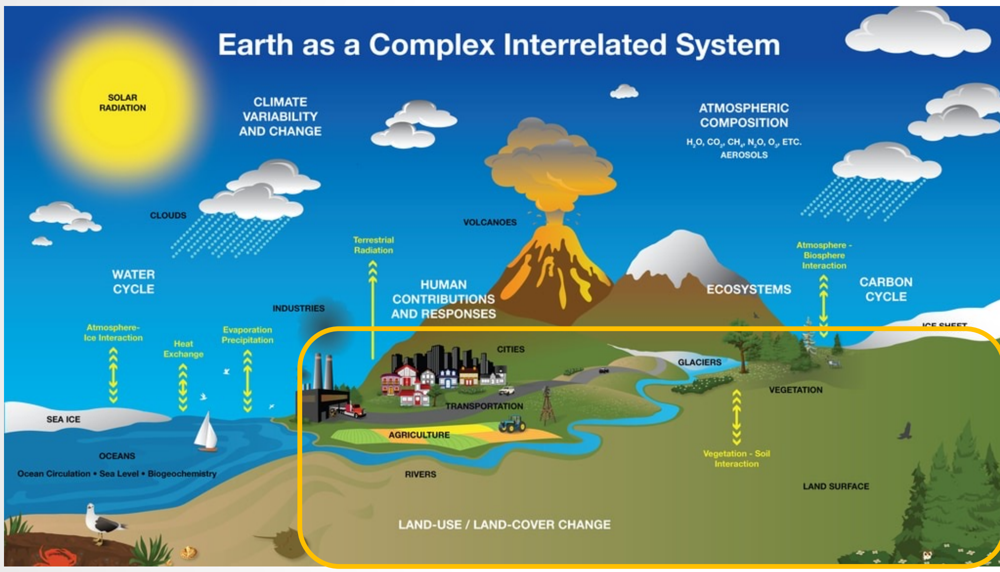


Figure SPM.8.a (IPCC report AR6 SPM)

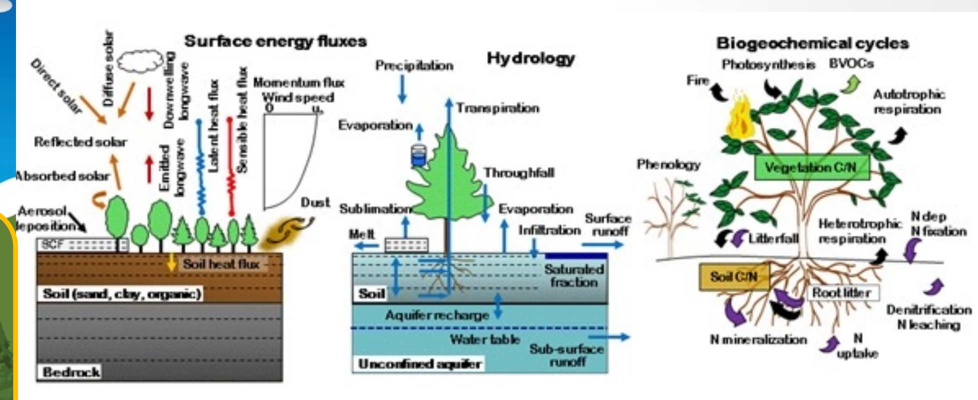
Simulating the natural processes of the terrestrial ecosystem



Energy cycle

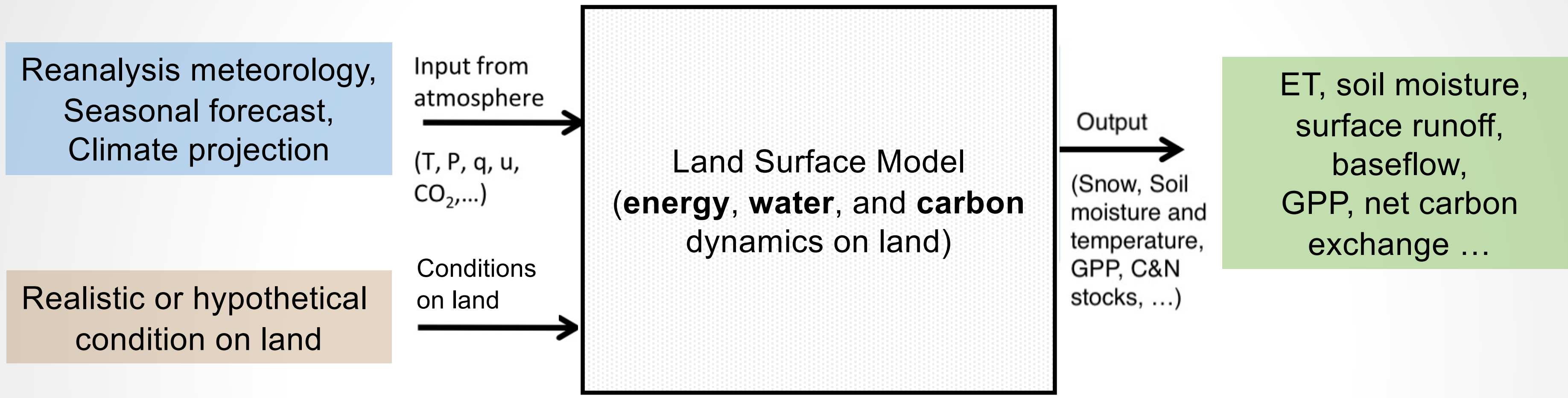
Water cycle

Carbon cycle



https://www.cesm.ucar.edu/models/clm

Land Surface Model (LSM)



- Inputs
  - **Meteorology** (e.g., air temperature, rainfall, radiation)
  - **Initial conditions on land** (e.g., status of vegetation, snow, and soil)
- Outputs
  - Water variables (e.g., soil water, runoff, baseflow)
  - Carbon variables (e.g., Gross Primary Production, Net carbon exchange)
- Use offline (if meteorology is prescribed) or coupled to the atmosphere in an ESM.

NASA's Catchment-CN land model

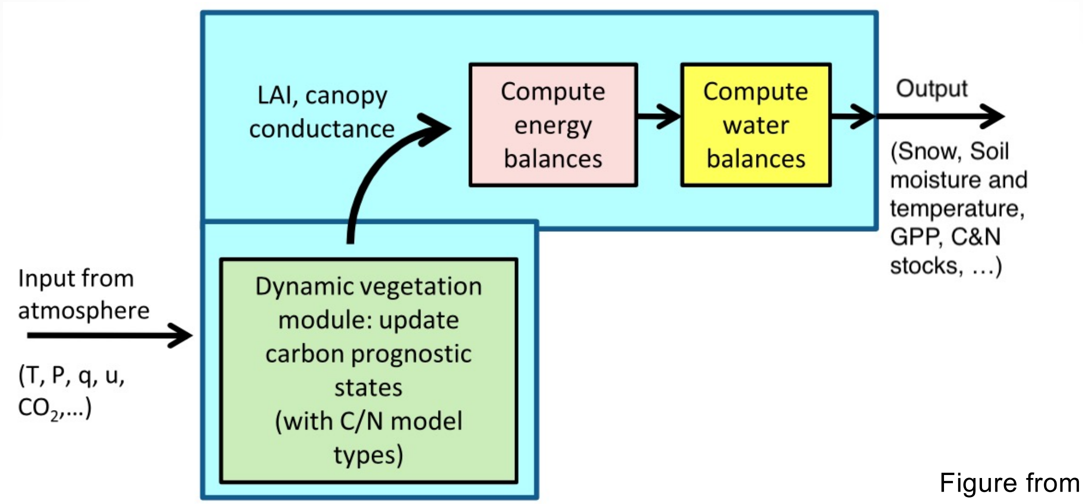


Figure from Koster et al. (2014)

- Use energy and water dynamics from Catchment model (Koster et al., 2000).
  - Dynamically treats the spatial variation within each hydrological catchment.
- Merged carbon and nitrogen dynamics from Community Land Model (v4, now v5.1).
- Energy and water dynamics at every 7.5 mins and carbon dynamics at every 90 mins.

S2S meteorological forecast

Weather forecast? Climate projection? Seasonal forecast?

- Forecast of meteorological states.
  - Temperature, precipitation, wind, radiation, humidity etc.

- However, time scale of interest varies.
  - Weather forecast: up to 5~10 days
  - Climate projection: several decades (e.g., year 2050) or a century (e.g., year 2100)
    - The classical averaging period is 30 years.
  - Seasonal forecasts: longer than weather forecast; up to several months

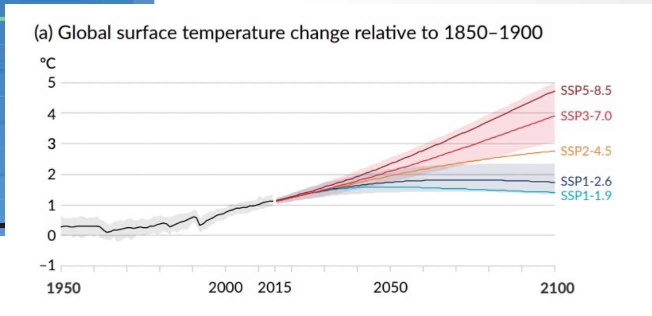
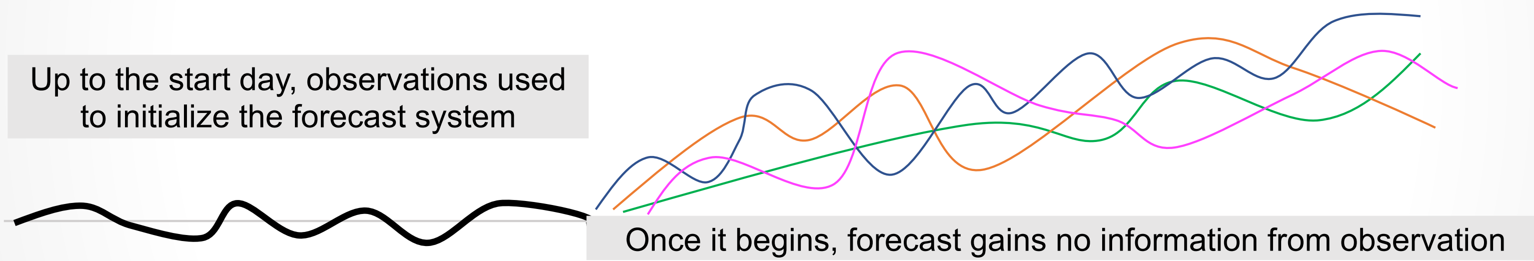


Figure SPM.8.a (IPCC report AR6 SPM)

NASA GMAO’s S2S meteorological forecast system

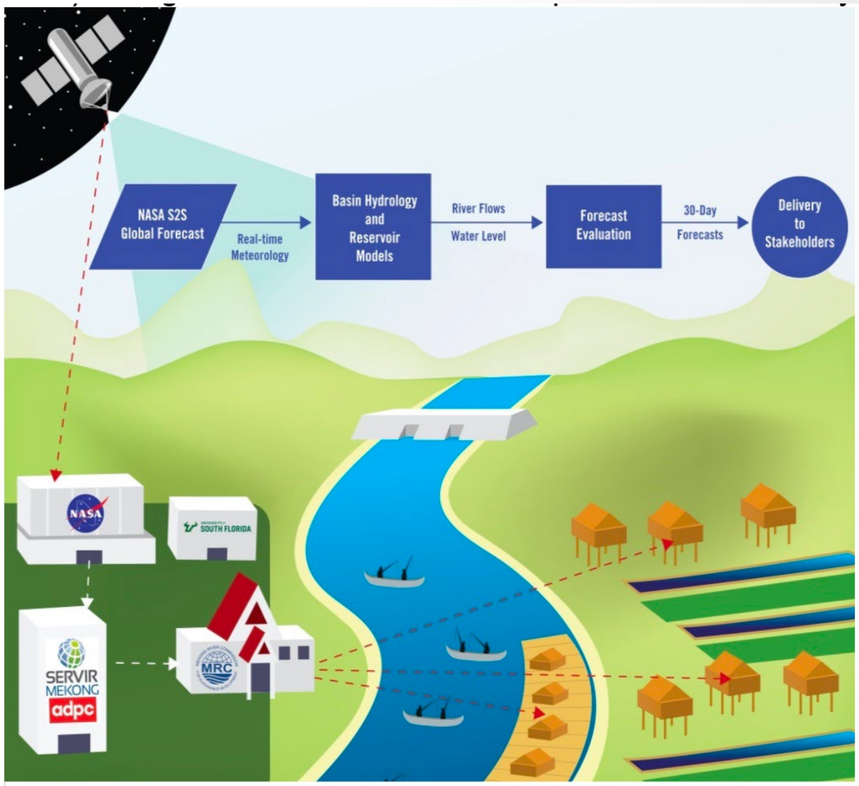
- Multiple projections (***<u>ensemble</u>*** forecasts) due to atmospheric chaos



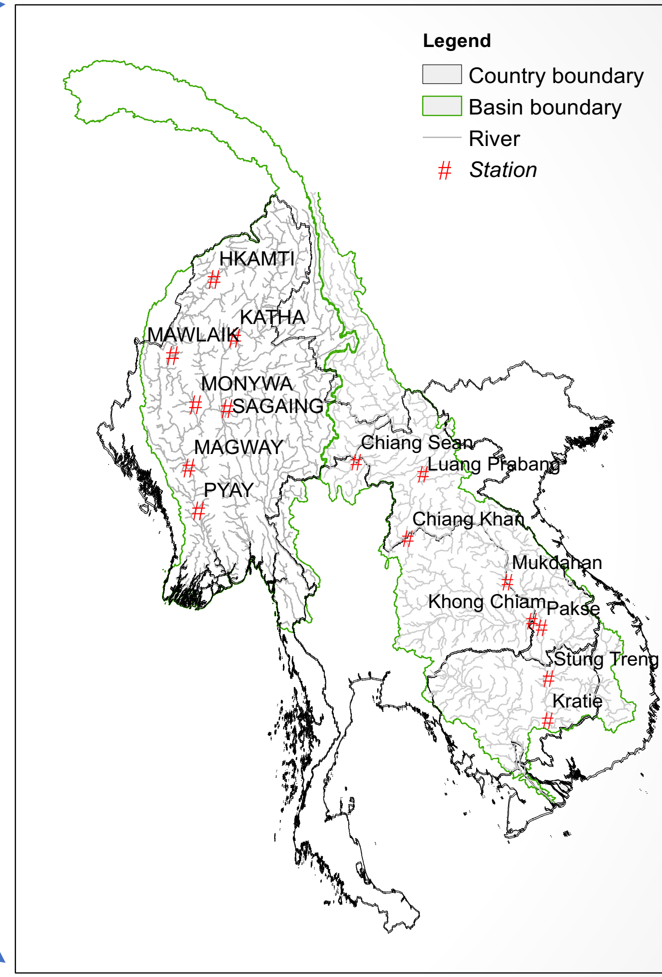
Application 1: Sub-seasonal forecast of river water availability

Developing sub-seasonal water availability forecasts for informed decision-making

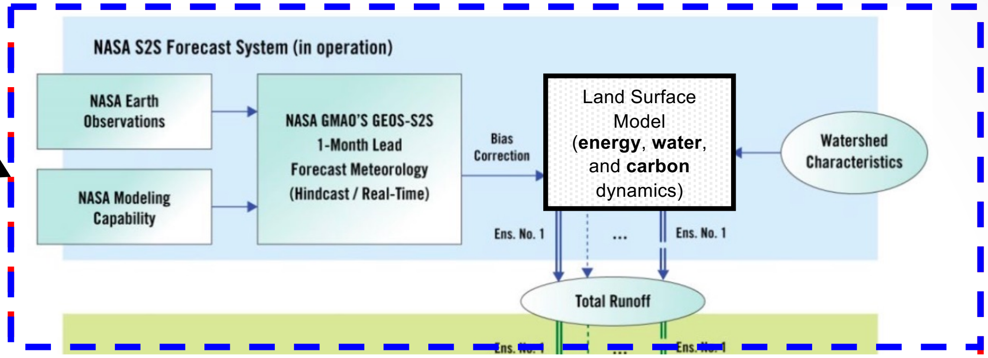
- NASA SERVIR Applied Science Team
- PI: Mauricio E. Arias (USF)
- Co-Is: Eunjee Lee, Randy Koster
- To improve the Mekong's water forecasts:
  - Use NASA's seasonal forecast to increase temporal coverage to 30 days
  - Account for reservoir operations
- To provide real-time water forecasts to support decision-making in water resources management.




SOUTHEAST
ASIA
National capital
Major city
Lake
International boundary
Mercator Projection
CHINA
MYANMAR
LAOS
THAILAND
VIETNAM
CAMBODIA
MALAYSIA
INDONESIA
PHILIPPINES
AUSTRALIA
South
China
Sea
Philippine
Sea
North
Pacific
Ocean
Indian Ocean
Borneo
Sumatra
Java
New Guinea
© Nations Online Project


Legend
Country boundary
Basin boundary
River
Station
HKAMTI
KATHA
MAWLAIK
MONYWA
SAGAING
MAGWAY
PYAY
Chiang Sean
Luang Prabang
Chiang Khan
Mukdahan
Khong Chiam
Pakse
Stung Treng
Kratie

Evaluation of streamflow forecast skill by applying retrospective seasonal forecast meteorology

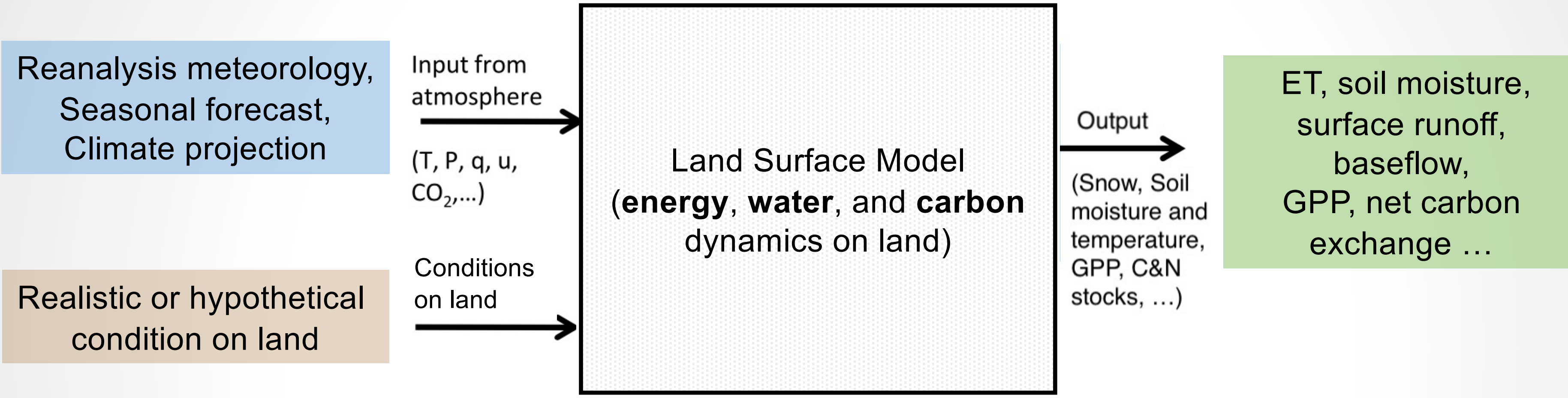


If you conduct this project, what would be your 1st task?

STEP 1

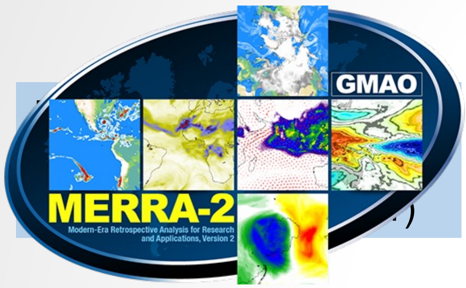
Evaluation of historical flow

Land Surface Model (LSM)



- Inputs
  - **<u>Meteorology</u>** (e.g., air temperature, rainfall, radiation)
  - **<u>Initial conditions on land</u>** (e.g., status of vegetation, snow, and soil)
- Outputs
  - Water variables (e.g., soil water, runoff, baseflow)
  - Carbon variables

Land Surface Model for evaluating carbon and water fluxes



Realistic condition on land

Input from atmosphere

(T, P, q, u, CO_2,…)

Conditions on land

NASA's Catchment-CN (**energy**, **water**, and **carbon** dynamics on land)

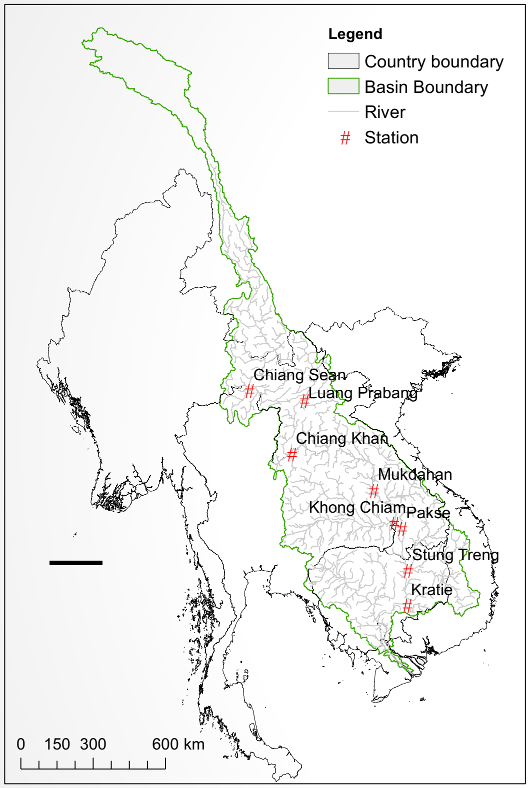
Output

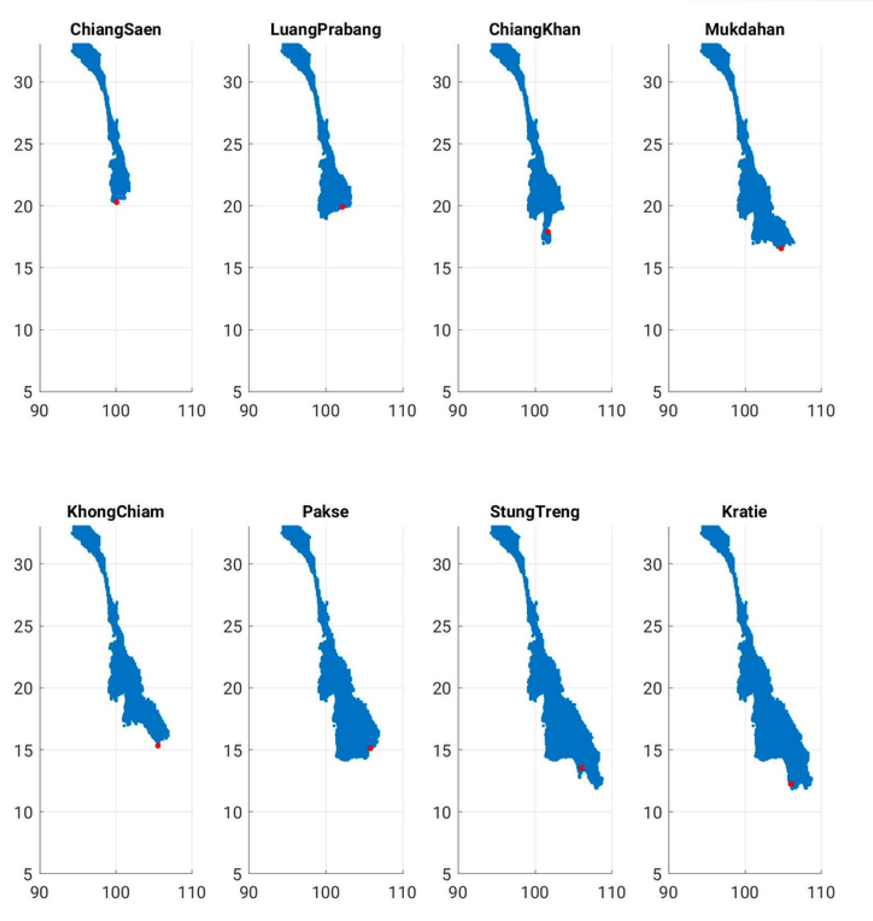
(Snow, Soil moisture and temperature, GPP, C&N stocks, …)

Realistic historical water fluxes

- Meteorological input: NASA GMAO's MERRA-2 reanalysis (0.5° × 0.625°)
- Computations performed on 9km equal-area grid (Brodzik et al., 2012)
- Different 9-km land elements below a 0.5° × 0.625° grid cell shares a same meteorological forcing. However, they behave differently due to differences in sub-grid heterogeneity (e.g., topographical character, vegetation type, soil type).
- Realistic water variables and carbon variables (e.g., surface runoff, GPP)

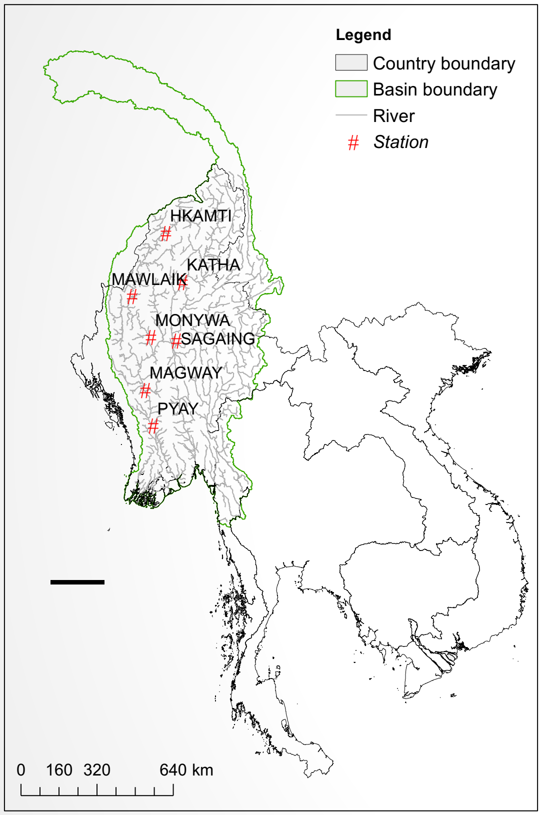
Catchment areas for Mekong gauges



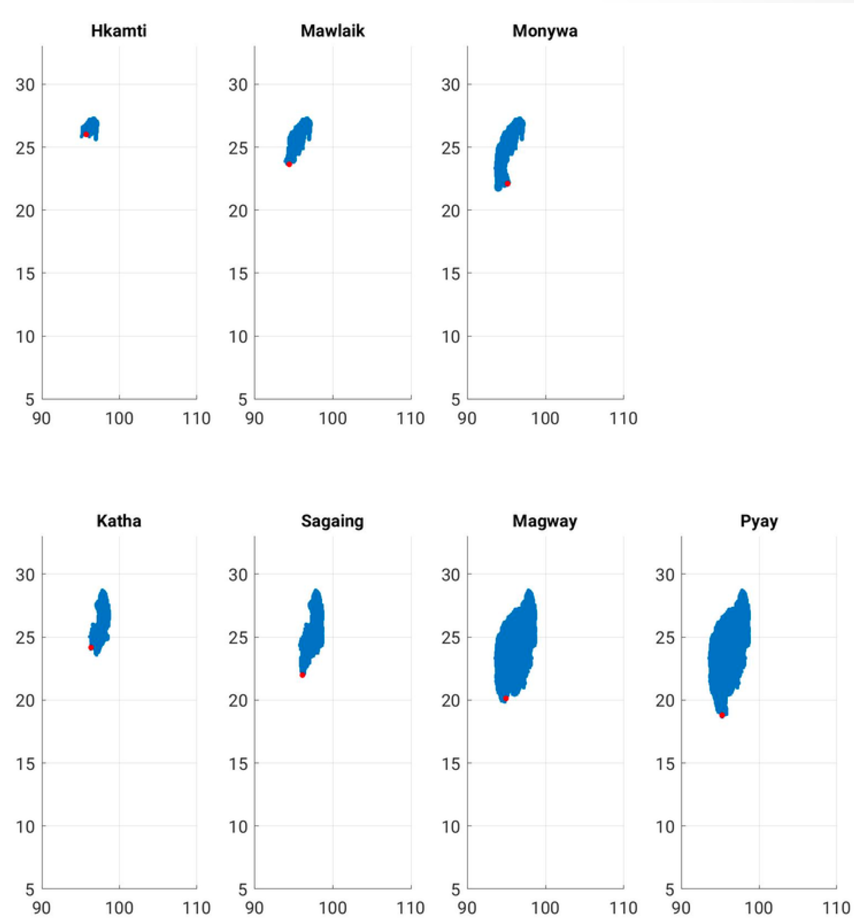


Catchment areas for Myanmar gauges

National Aeronautics and Space Administration



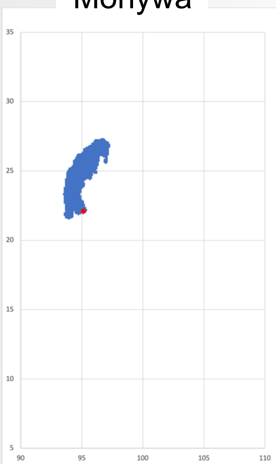
Hkamti, Mawlaik, Monywa : Chindwin river
Katha, Sagaing, Magway, Pyay : Irrawaddy river

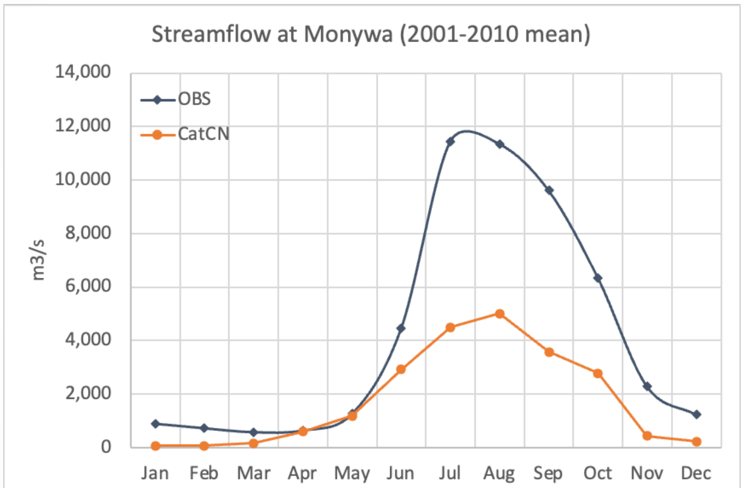


Aggregated total runoff at Monywa

Forced with MERRA-2 precipitation
(corrected by CPCU gauge data)

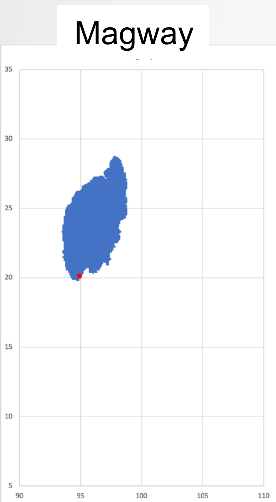
Monywa

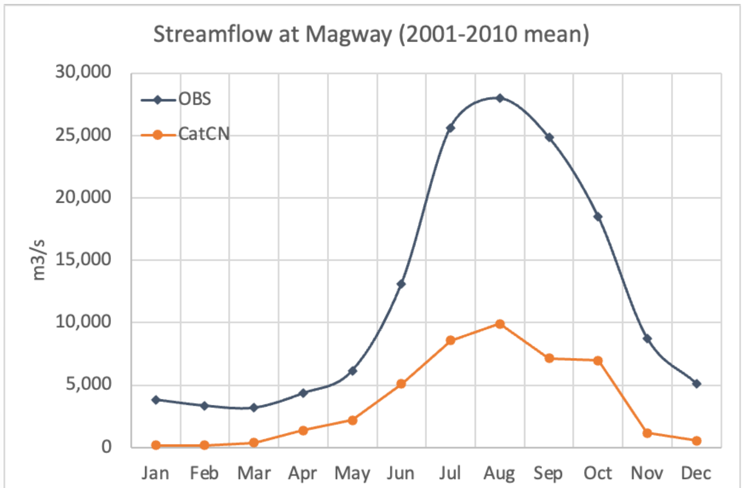




Aggregated total runoff at Magway

Forced with MERRA-2 precipitation
(corrected by CPCU gauge data)

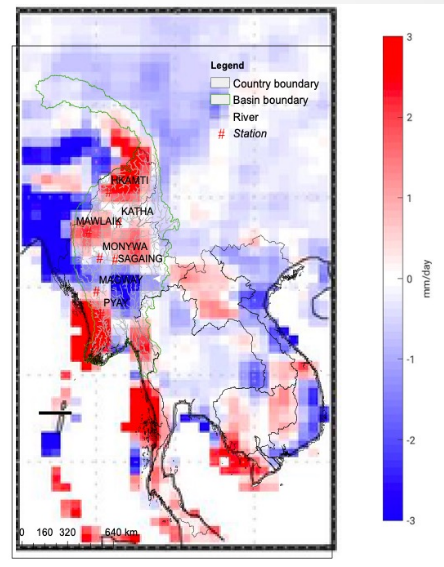




National Aeronautics and Space Administration

- When being forced with the MERRA-2 reanalysis precipitation, the model significantly underestimated historical runoff at the gauges in Myanmar.
  - *"The poor skill in the reanalysis products in Myanmar can be traced back directly to errors in the CPCU precipitation, which stem from persistent errors in the input gauge measurements from Myanmar prior to May 2008" (Reichle et al. 2017).*

- For the area covering Myanmar, we applied an alternative precipitation corrected by the satellite-based IMERG product.
  - The IMERG algorithm combines information from the Global Precipitation Measurement (GPM) satellite to estimate precipitation over the majority of the Earth's surface (https://gpm.nasa.gov/data/imerg).

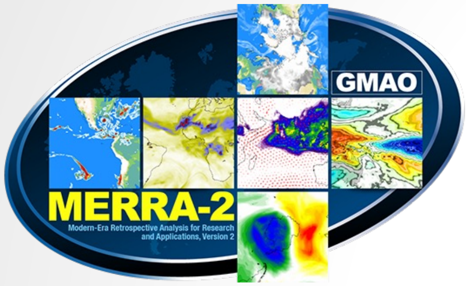


Anomaly of the 2001-2020 average precipitation

* IMERG: Integrated Multi-satellitE Retrievals for GPM

Modeling historical water fluxes

Precipitation corrected by IMERG



Realistic initial land status

Input from atmosphere

(T, P, q, u, CO_2,…)

Conditions on land

Catchment-CN (**energy**, **water**, and **carbon** dynamics on land)

Output

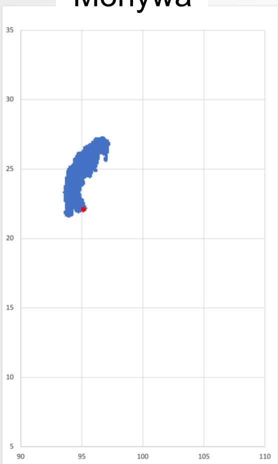
(Snow, Soil moisture and temperature, GPP, C&N stocks, …)

Runoff

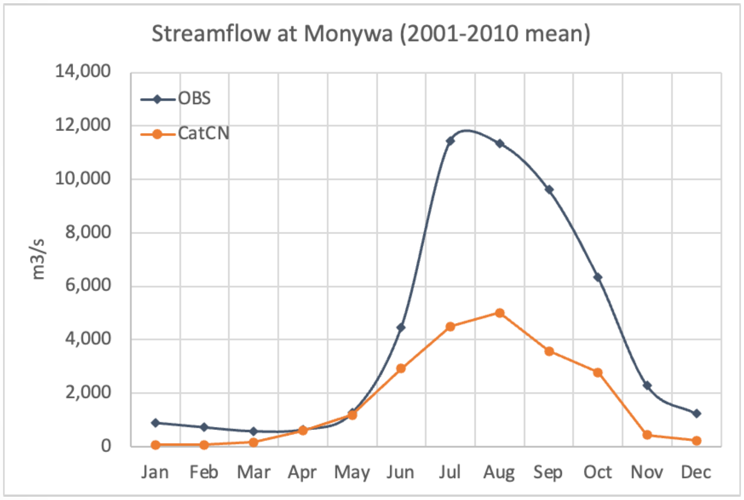
- Meteorological input: NASA GMAO's MERRA-2 reanalysis and precipitation corrected by IMERG
- Computations performed on 9km equal-area grid (Brodzik et al., 2012)
- Model runoff evaluated against streamflow at gauges in Myanmar.

Aggregated total runoff at Monywa

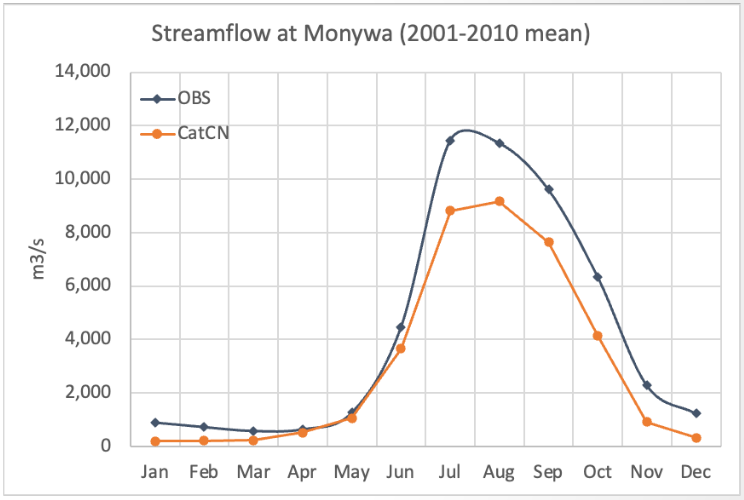
Monywa



Forced with MERRA-2 precipitation
(corrected by CPCU gauge data)



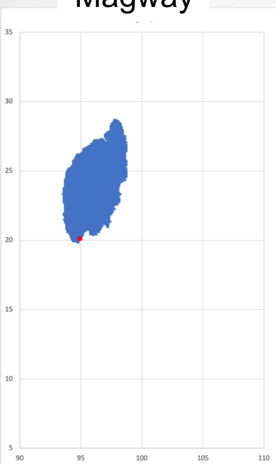
Forced with revised precipitation
(corrected by IMERG)



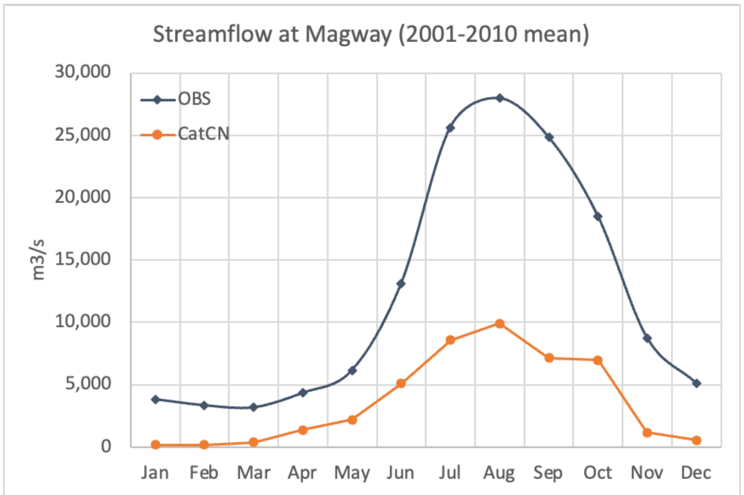
Aggregated total runoff at Magway

National Aeronautics and Space Administration

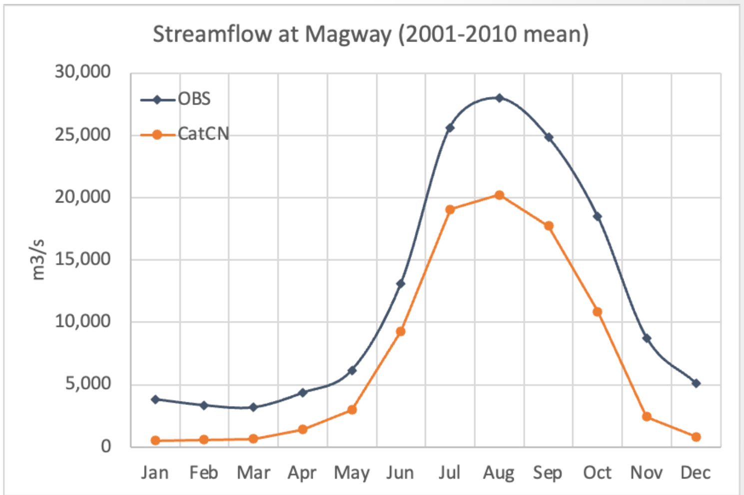
Magway



Forced with MERRA-2 precipitation (corrected by CPCU gauge data)



Forced with revised precipitation (corrected by IMERG)



By applying the rainfall corrected by IMERG, the aggregated model runoff shows better agreement (right panels) with the observed discharge at the Myanmar gauges.

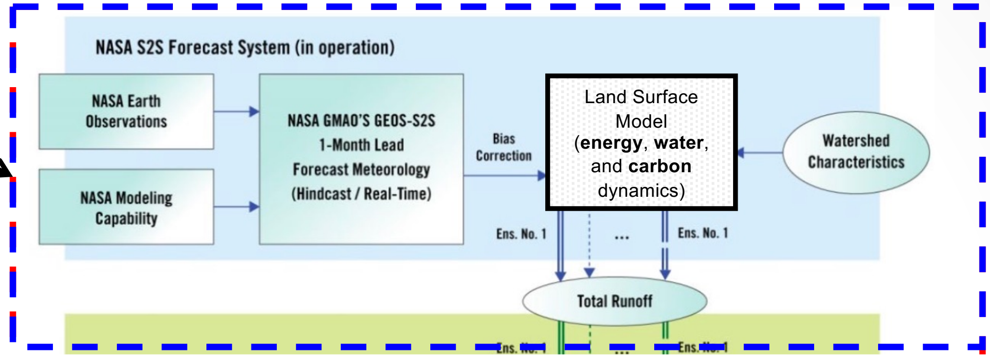
Follow-up question

If we apply the rainfall data corrected by satellite measurement for bias-correction of input forecast rainfall and preparation of initial land condition, will it also improve the skill to forecast streamflow?

STEP 2

Evaluation of retrospective (hindcast) forecast streamflow

Evaluation of streamflow forecast skill by applying retrospective seasonal forecast meteorology



National Aeronautics and Space Administration

NASA's GEOS S2S meteorological forecasts


National Aeronautics and Space Administration
Goddard Space Flight Center

GO

Earth Sciences Division | Sciences and Exploration

Global Modeling and Assimilation Office

GMAO

WEATHER ANALYSIS & PREDICTION | SEASONAL-DECADAL ANALYSIS & PREDICTION | REANALYSIS | GLOBAL MESOSCALE MODELING | OBSERVING SYSTEM SCIENCE

- GEOS Sub/Seasonal Project
- Data Access
- Documentation
- Forecasts
- Highlights
- Outreach
- Publications
- Seasonal-Decadal Page

GEOS Sub-seasonal / Seasonal Project, Version 2

Project Overview

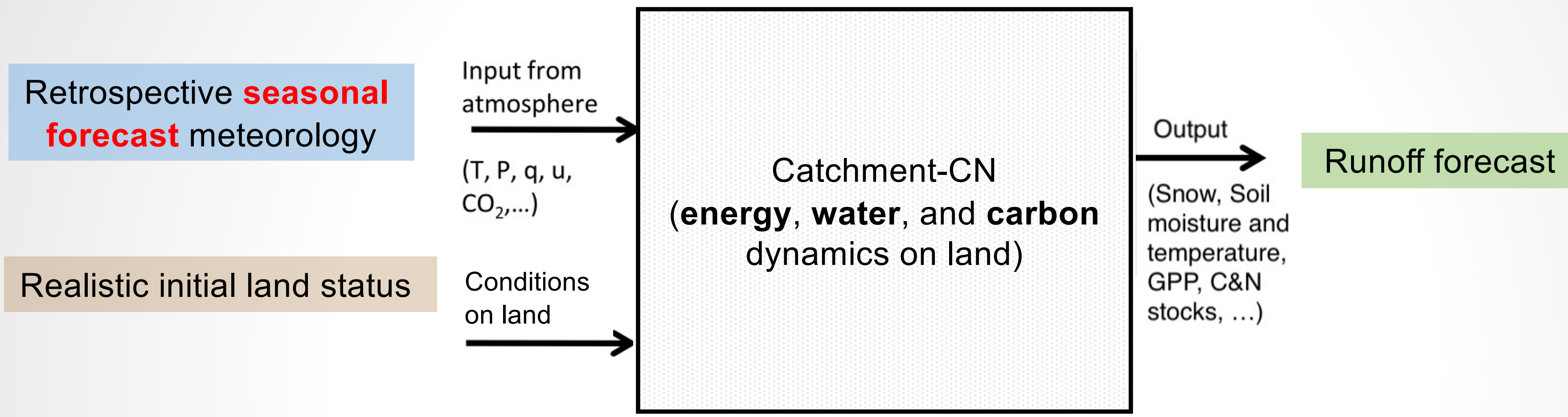
The NASA GMAO seasonal forecasts are produced with the Goddard Earth Observing System (GEOS) AOGCM (GEOS-S2S_2.1). The atmospheric component (Rienecker et al. 2008; Molod et al. 2015) is discretized on a cubed sphere grid (Putman and Lin, 2008) at approximately ½ ° horizontal resolution with 72 vertical layers. The current version includes the recently developed two-moment cloud microphysics and an interactive aerosol model. The ocean component is version 5 of the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model (MOM5) (Griffies 2012), discretized on a tripolar grid and run at a horizontal resolution of approximately ½ ° with 40 vertical layers.

The land component is the Catchment Land Surface Model (Koster et al. 2000). Sea ice is represented with the Los Alamos Sea Ice model (CICE4) (Hunke and Lipscomb 2010). The system is initialized using MERRA-2 atmospheric reanalysis (Gelaro et al. 2017) and the GMAO Interim Ocean Analysis. The analysis incorporates sub-surface temperature and salinity data from available CTDs and Argo floats, temperature data from XBTs and moored arrays, and along-track altimetry. The analysis is nudged to the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA, Donlon et al. 2012) sea surface temperatures, and uses the EUMETSAT OSI-SAF sea ice concentration provided with OSTIA. Sea ice thickness is model-derived. Ensemble members are produced with initial states at 5-day intervals, with additional members at the end of the month based on perturbations of the atmospheric and ocean states.

https://gmao.gsfc.nasa.gov/seasonal/GEOS-S2S/

- Meteorological variables from NASA GMAO's S2S forecast system are predicted at leads out up to several months.
- Spatial resolution: 0.5° lat x 0.5° long
- Temporal resolution: daily
- Current version (v2): initialized at every 5 days.
- Upcoming version (v3): up to 40 ensemble members per month.

Forecasting sub-seasonal water fluxes



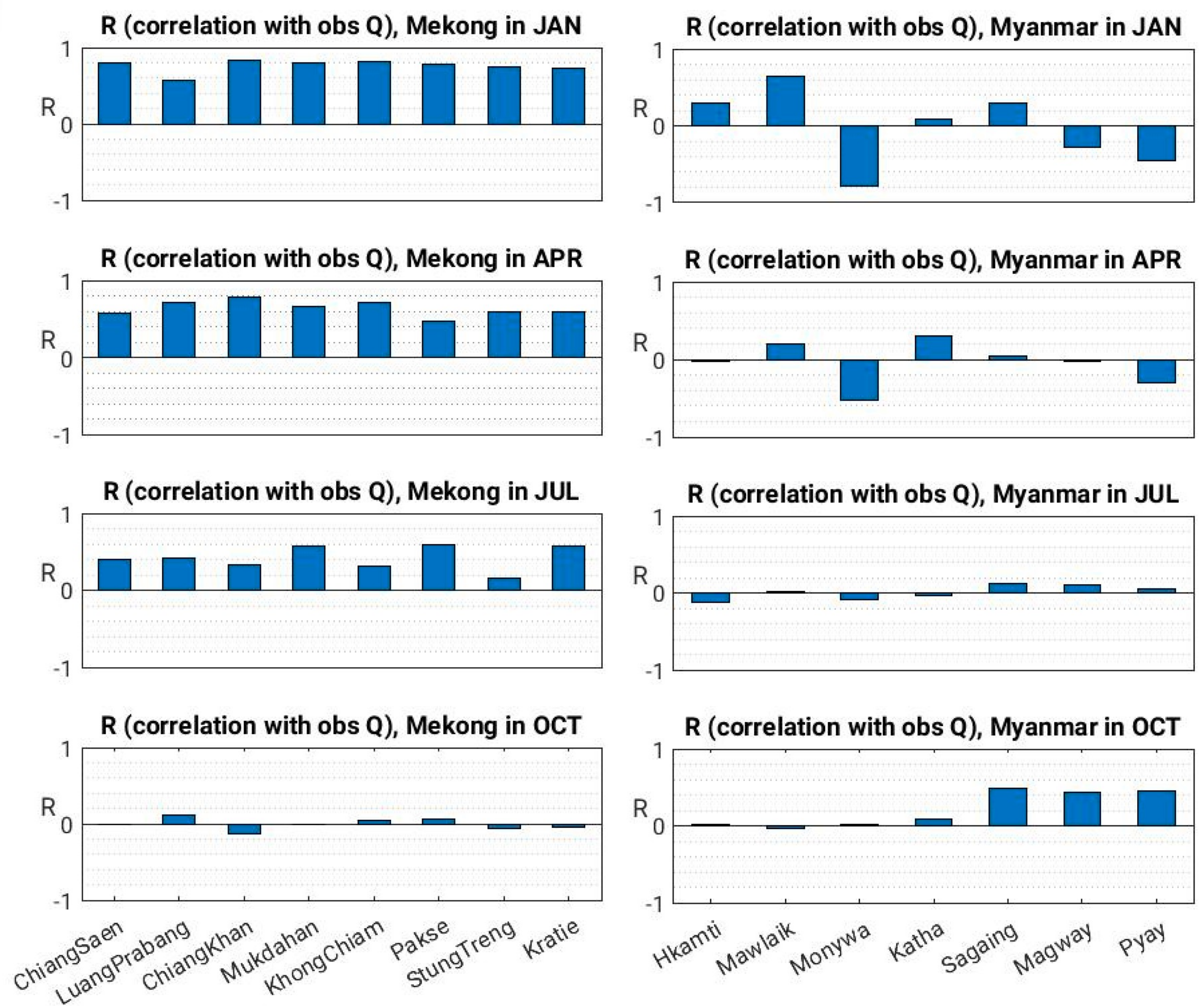
- Inputs to the land model
  - ***Bias-corrected, retrospective seasonal forecast meteorology***
  - Realistic initial condition of land (e.g., snow cover, soil moisture, soil temperature)
    - Extracted from a long-term offline Catchment-CN simulation, driven with MERRA-2 reanalysis meteorological forcing (Lee et al., 2018).
- Outputs from the land model
  - Retrospective ensemble runoff forecasts up to several months

Experimental design

	Winter	Spring	Summer	Fall
Initialization date of forecast meteorology (4 ***ensemble members***)	December 27	March 27	June 30	September 28
Offline Catchment-CN simulation start date (each year for 2001-2020)	January 1	April 1	July 1	October 1
Target period of analysis (1st forecast lead month)	January (Jan 1 – 31)	April (Apr 1 – 30)	July (Jul 1 – 31)	October (Oct 1 – 31)

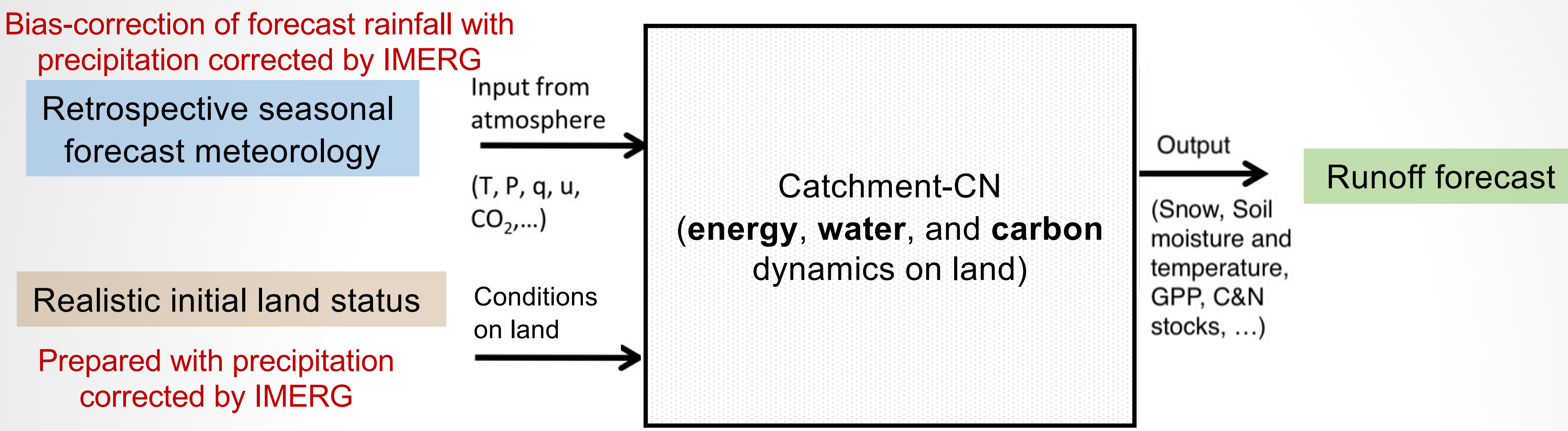
Evaluation metric of the forecast skill
=> Time-series correlation coefficient (Pearson's r) of 20 pairs (2001-2020) between forecast and observation at the 1st forecast lead month

Streamflow forecast skills (at the 1st lead month)



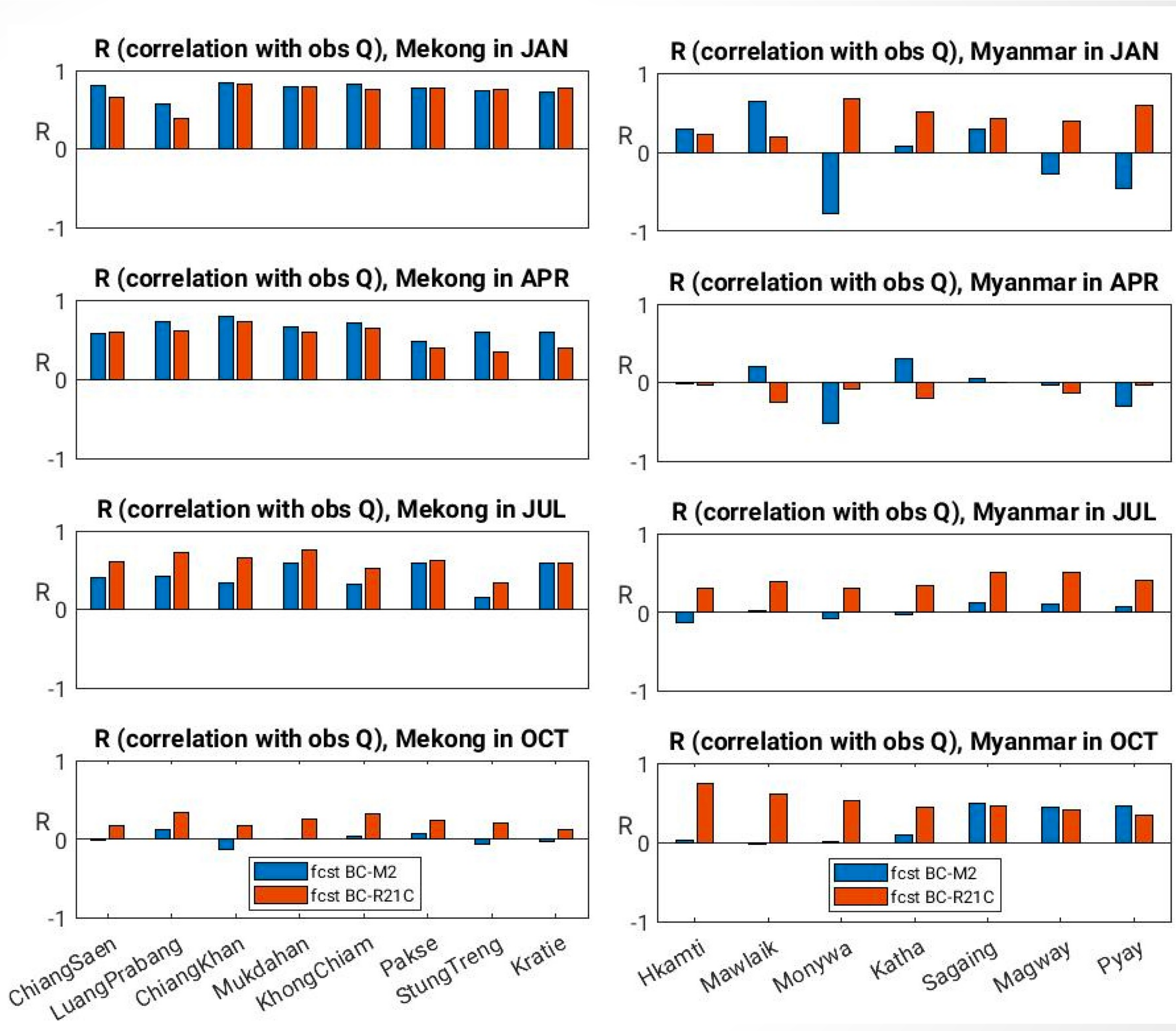
However, the streamflow forecast skill compared at Myanmar gauges were very low…

Forecasting sub-seasonal water fluxes



- Inputs to the land model
  - Bias-corrected (with R21C precipitation), retrospective seasonal forecast meteorology
  - Realistic initial condition of land (e.g., snow cover, soil moisture, soil temperature)
    - Extracted from a long-term offline Catchment-CN simulation, driven with MERRA-2 reanalysis meteorological forcing and R21C precipitation.
- Outputs from the land model
  - Retrospective ensemble runoff forecasts up to several months

Improved streamflow forecast skills (at the 1st lead month)

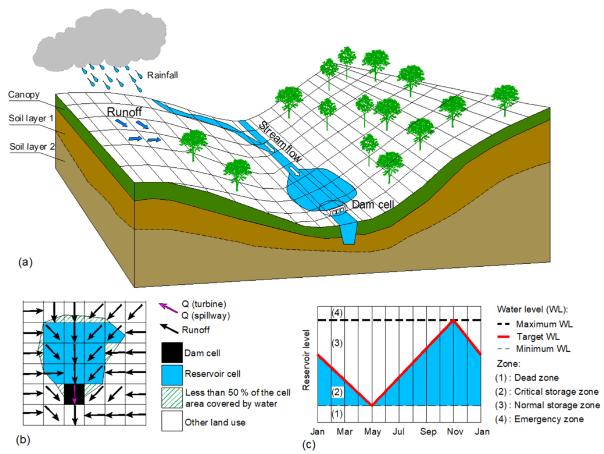


Blue: bias-correction and initial land condition prepared by MERRA-2 precipitation

Red: bias-correction and initial land condition prepared by precipitation corrected by IMERG

Summary of sub-seasonal water forecast study

- We demonstrate improved river water availability forecast within the 1st lead month at southeast Asia, by applying the precipitation corrected by IMERG for bias-correction of forecast rainfall and preparation of land's initial condition.
- Our results demonstrate usefulness of satellite data for regional streamflow forecasts, especially at the areas where gauge-based rainfall measurements are of poor quality.
- Further improvement can potentially be achieved by integrating river routing and reservoir operations into the sub-seasonal water forecast system (a part of the proposed task).



Application 2: Seasonal forecast of land's carbon uptake

Seasonal Carbon forecast

- New area of research

- *Carbon forecasting*, in general, has been addressed only in a few studies.

(e.g., Rousseaux and Gregg, 2017; Park et al., 2019; Séférian et al., 2018; Lovenduski et al., 2019)

- Why do we care about the seasonal carbon forecast?
  - To improve future S2S forecast system, we need the information about how the system will behave with the carbon cycle.
  - Carbon forecasts can eventually support a wider range of end users in fire management, forestry, and agriculture.

- Research objectives
  - To evaluate carbon forecast skill by utilizing S2S forecasts and a land surface model against a fully independent, remotely-sensed GPP dataset
  - To explore straightforward physical mechanisms

Land Surface Model (LSM) for forecasting carbon fluxes

Retrospective **seasonal forecast** meteorology

Input from atmosphere

(T, P, q, u, CO_2,…)

Realistic initial land status on Jan 1st
Lee et al. (2018)

Conditions on land

NASA's Catchment-CN
(**energy**, **water**, and **carbon** dynamics on land)

Output

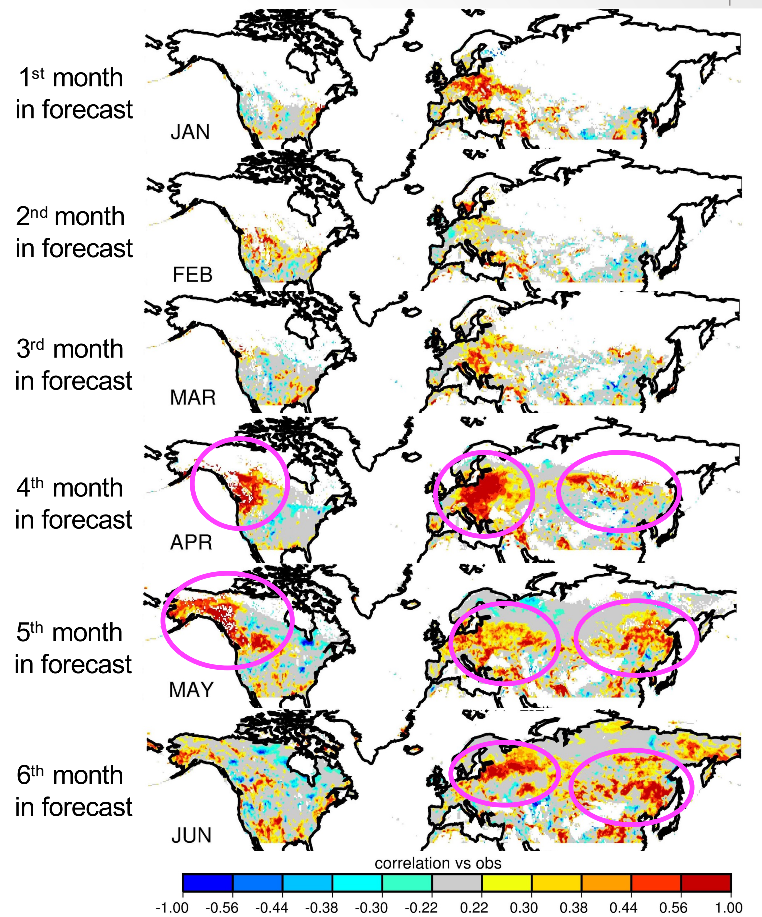
(Snow, Soil moisture and temperature, GPP, C&N stocks, …)

Retrospective forecast of **carbon (GPP)** for **9 months** 2001-2020

- Forced with bias-corrected, retrospective seasonal forecast meteorology.
- Ensemble carbon forecasts (Jan 1st – Sep 30th) generated by Catchment-CN
- Evaluated with FluxSat GPP derived from MODIS reflectances (Joiner et al., 2018)
- Temporal correlation coefficients of 20 pairs (2001-2020) between forecast and obs.

Skillful forecast of land's carbon uptake

- Skillful GPP forecast in northwestern North America, eastern Europe, and Eurasia.
- High forecast skill in April, May, and June.
- Meteorological forecast skill does not explain the high carbon forecast skill after 3rd lead month.
- Other factors must contribute to the carbon forecast in mid- and high-latitudes during spring.



0.22, 0.30, 0.38, 0.44, and 0.56 being statistically different from zero at the 66.7%, 80%, 90%, 95% and 99% confidence levels, respectively.

Lee et al. (2022). *Geophys. Res. Lett.*

Snowcover removal timing and a supplemental experiment

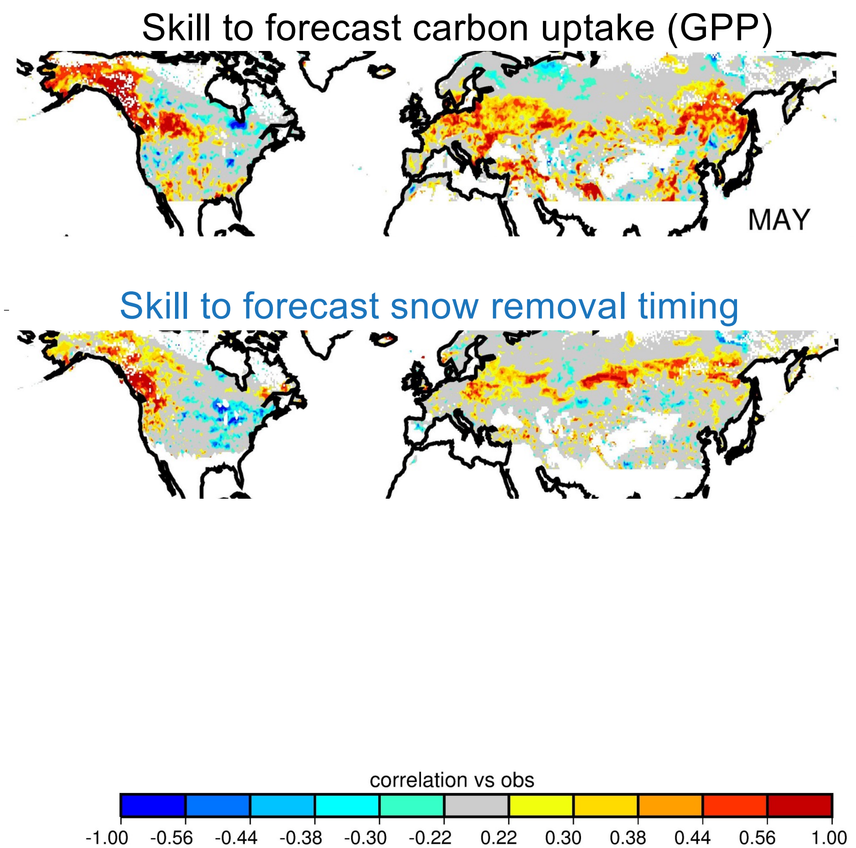
- Snow cover removal day was defined as:
  - When daily snow mass becomes lower than 1 kg/m^2 (or 1 mm of snow water equivalent (SWE)) and,
  - The snow mass remains below the threshold for the following 7 consecutive days

- EXP suite
  - Same as CTRL, except for retaining the inter-annual variation of the CN initialization on Jan 1^{st} and fixing other conditions as those in year 2013.
  - No inter-annual variability in forecast meteorology and snow and soil moisture initialization is allowed.

Lee et al. (2022). *Geophys. Res. Lett.*

Contributions from snow and carbon initializations

- Contribution of snow initialization
  - Northwestern N. America and Eurasia.
  - Snowpack initialized in January sits undisturbed until the snow melts away.
  - Help determine when the carbon uptake begins by vegetation.
- Contribution of carbon initialization
  - Southeastern Europe and eastern Asia.
  - Carbon storage represents relatively "slow" component of the Earth system.
  - Help set the stage for plant productivity.



Lee et al. (2022). *Geophys. Res. Lett.*

Effects of snow initialization and CN initialization on seasonal carbon forecast skill

Snow initialization

- Snowpack initialized in January sit undisturbed on the surface until the spring snow-melt season.
- The information contained in the initial snowpack provides a latent predictability to the climate system (Guo et al., 2012), helping determine when the snow will finally melt away and spring vegetation growth (carbon uptake) can begin.

Carbon & Nitrogen initialization

- Another potential source of GPP forecast skill.
- The storage of carbon and nitrogen represents another relatively "slow" component of the coupled Earth system.
- Vegetation places carbon and nitrogen in different reservoirs partly for use in later production. Thus, the vegetation's established storage distribution helps set the stage for plant health and productivity during the subsequent year.

Lee et al. (2022). *Geophys. Res. Lett.*

Summary of seasonal forecast skill of land carbon uptake

1. This study demonstrate an ability to accurately forecast spring-summer carbon uptake at multi-month leads.
2. The result highlights the significance of land initialization in seasonal carbon forecasts.
3. The delay associated with the snow initialization is a notable lead (three to five months) for forecast skill realization. Much of the snowpack sits undisturbed on the surface until the spring snowmelt season, providing a latent predictability to the forecast system.
4. Carbon reservoirs initialization is also important in certain key regions and at later forecast lead months.
5. In central-eastern Eurasia, soil moisture and snow initialization may both contribute to GPP forecast skill in part by controlling growing season moisture variability.
6. Snowpack initialization and carbon reservoir initialization provide contributions to GPP forecast skill in largely complementary areas.